Complex interactions and applications to sustainable design

Nick McCullen
School of Mathematics
University of Leeds

Department of
Architecture and Civil Engineering
University of Bath
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Research interests

Career history

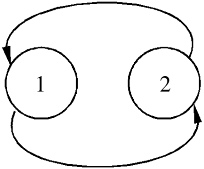
1. Ph.D.: Chaos in coupled systems. 2003–2007
2. PDRA: Emergence in complex systems. 2007–2009
3. Research Fellow: Energy and complexity. 2010–2012

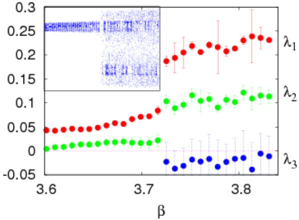
Research vision

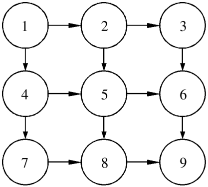
- Use complex systems thinking,
- link people, technology and environment,
- strong interdisciplinary background.

Coupled nonlinear systems

- Synchronisation of chaotic oscillations[1],
- sensitive signal detection using feed-forward coupling[2],
- experimental, numerical & data analysis[3],







- Application to distributed generation.

[1] **McCullen** and Moresco, Phys. Rev. E, (2011)
[2] **McCullen**, Mullin & Golubitsky, Phys. Rev. Lett., (2007)
[3] **McCullen** and Moresco, Phys. Rev. E, (2006)

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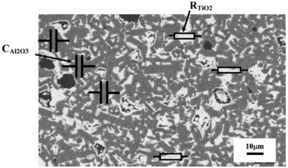
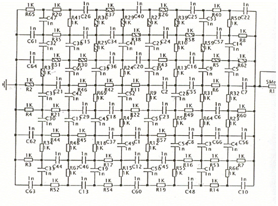
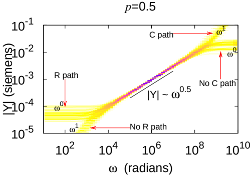
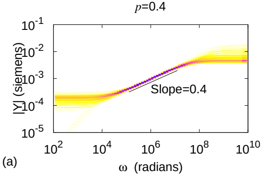
Complex network models

Models of composite materials[4]:









- Explained power-law dependence of conduction on component ratio[5].

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[4] **McCullen**, Almond, Budd and Hunt, J. Phys. D, (2009)

[5] Almond, Budd, Freitag, Hunt, **McCullen** and Smith, *Sub. to Physica A*, (2012)

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Energy and complexity

- Interdisciplinary collaboration between Mathematics, Engineering, Earth & Environment and city stakeholders.
- applying complexity science tools to city-level energy decision-making,
- dynamical systems modelling of consumer behaviour[6],
- study energy technology diffusion via social networks,
- aim to recommend targeting strategies for optimising chance of roll-out success.

[6] **McCullen**, Ivanchenko, Shalfeev and Gale, Int. J. Bif. Chaos, (2011)

Network models

- Various complex network models exist to reproduce empirical observations.

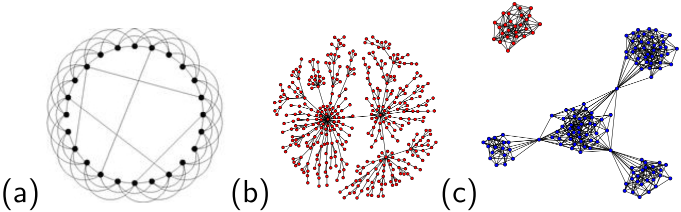
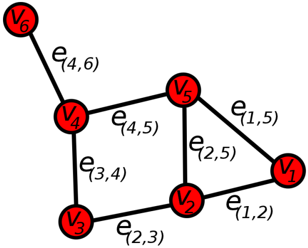


Figure: (a): *Small world* network. (b): Preferential attachment model. (c): Community structured model.

- We use these to model technology diffusion mediated via social network interactions.

Dynamical models on networks

- Individuals are considered as *nodes* on a network.
  - Properties of nodes are associated with variables.
- *Links* ('edges') transmit information between individuals.



- Dynamical equations determine system evolution.

Modelling uptake of energy technology

- Decision of individuals to adopt a particular technology based on combination of factors:
  - personal + social benefit.
- Intrinsic benefits to individual.
- Social benefit combination of both:
  - personal social network – friends & neighbours,
  - mainstream social norm (society as a whole).

Mathematical model

- Total *utility* to individual:

$$u_i = \alpha_i p_i + \beta_i s_i + \gamma_i m \tag{1}$$

- p_i, s_i, m: personal, peer-group and societal influence.
- $\alpha_i, \beta_i, \gamma_i$: relative weightings given to each factor,

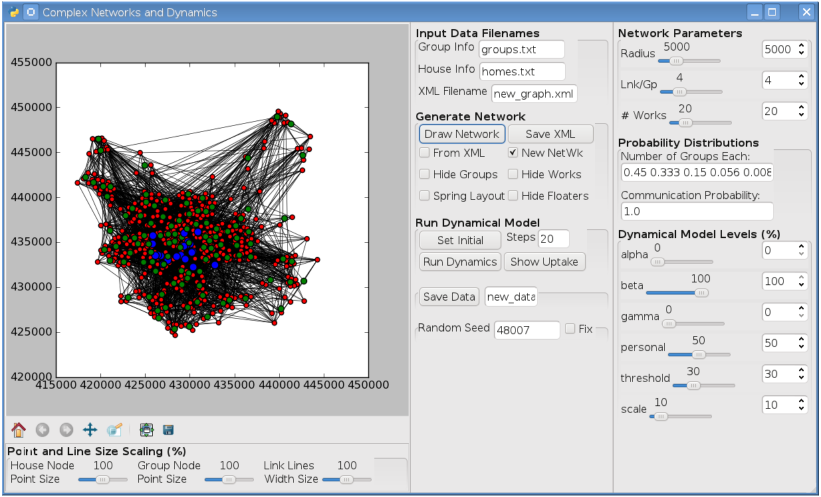
Households are nodes on a complex network, each with variable for current state, $x_i = 0, 1$.

$$\text{future state: } x_i' = \begin{cases} 1 & \text{if } x_i = 1, \\ 1 & \text{if } x_i = 0 \text{ and } u_i > \theta_i, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

- θ_i: threshold (barriers, costs etc.)

Implementing the model

Programmed in *Python*:



Computational results

Chance of success depends on model parameters:

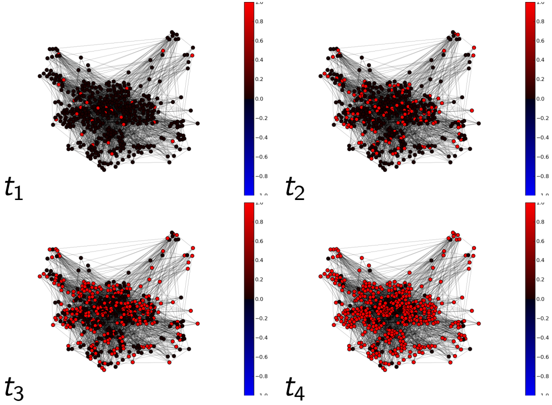
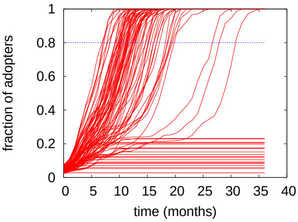
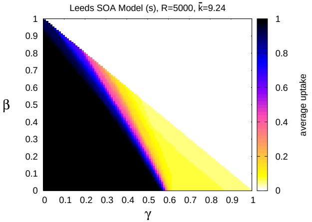


Figure: $t_{1,2,3,4} = 0, 4, 9, 27$





Future research direction

Bring complex systems thinking into energy management and low-carbon design:

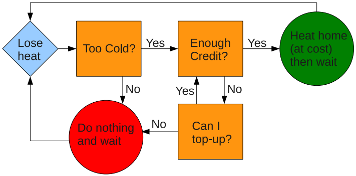
- whole system thinking applied to real-world problems,
- understand interaction of people and technology,
- interdisciplinary collaboration, using real data.

Role of the occupant in low-carbon design

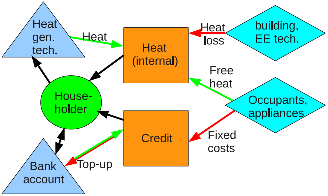
Models based on energy–budget management.

- Conceptual models:

Decision chart



Influence map



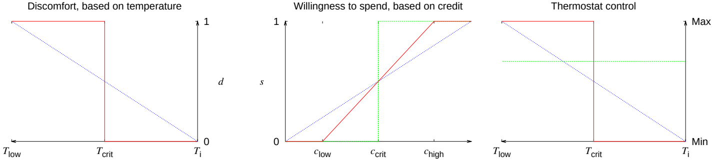
- Integrate building physics with user behaviour.

Model formulation

Algorithm for computations:

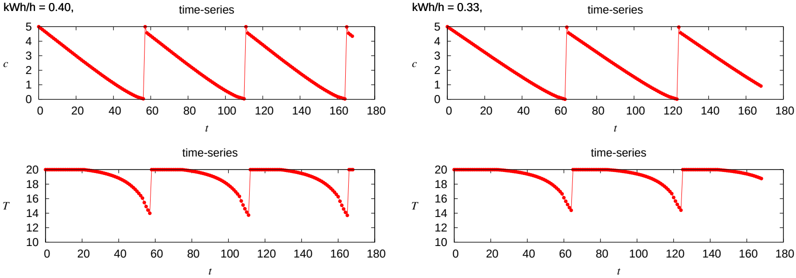
1. temperature T is compared to ideal,
2. credit c determines level of action,
3. temperature is raised by ΔT, at cost Δc,...

Example responses (different colours):



Toy example: rebound effect

Pre-Insulation **Insulation: 20% cut**

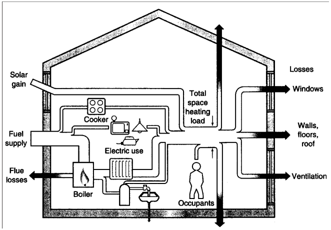


Assuming fixed cost of £$0.133/kWh$:

- Actual cut $= \frac{kWh_{pre} - kWh_{post,actual}}{kWh_{pre}} \approx 0.175$.
- *Rebound* of $\approx 12.5\%$ not going into CO_2 reduction.

Including building physics

- **Energy balance**: $Q_{loss} = Q_{gain}$.

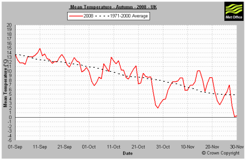


BREDEM-12, Anderson, B. R. *et al.*, BRE (2001)

losses: $Q_{loss} = Q_{cond.} + Q_{vent.}$ *gains:* $Q_{gains} = Q_{free} + Q_{gen.}$,

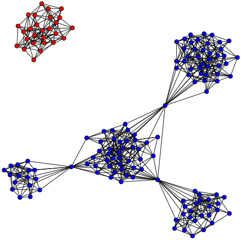
- $Q_{cond.} = \sum_i A_i(T - T_0)$,

Towards a whole-systems approach



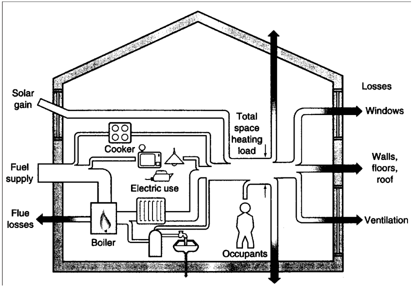
1. Include weather data,

   ⇒ extreme temperatures.
2. Smart-meter **network** interaction.
3. Demand management & smart grids:
   - interaction of user ⇔ technology,
   - complex system approach.



Teaching a whole systems approach to design

1. Mathematical sciences (UG):
    - building physics,
    - experimental techniques,
    - mathematical methods.
2. Complex systems (PG):
    - theory & modelling.
3. Computing:
    - designing models,
    - programming,
    - Python, LaTeX...



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